

Epidemiologic Studies on Short-Term Effects of Low Levels of Major Ambient Air Pollution Components

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Since the development of the World Health Organization (WHO) Air Quality Guidelines for Europe, a large number of epidemiologic studies have been published documenting effects of major air pollutants on health at concentrations below existing guidelines and standards. In this review, recent studies are discussed that permit some evaluation of short-term health effects observed at exposure levels lower than the current WHO Guidelines or U.S. Environmental Protection Agency (U.S. EPA) standards. Some studies have been conducted at concentration levels that never exceeded existing guidelines or standards. Other studies have been conducted at exposure levels sometimes exceeding current guidelines or standards. The published analyses of several of these studies permit evaluation of low-level health effects either because analyses were restricted to levels not exceeding the guidelines or graphic analyses were reported suggesting effects at these low levels. For ambient ozone, effects on lung function of subjects exercising outdoors have now been documented at 1-hr maximum levels not exceeding 120 $\mu\text{g}/\text{m}^3$, i.e., half the current U.S. EPA standard. One study even suggests that such effects occur at levels below 100 $\mu\text{g}/\text{m}^3$. Several studies are now available documenting effects of particulate air pollution on health in the virtual absence of SO_2 . Effects on mortality and hospital admissions for asthma have been documented at levels not exceeding 100 $\mu\text{g}/\text{m}^3$, expressed as 24-hr average inhalable particles PM10 concentration. Effects on lung function, acute respiratory symptoms, and medication use have been found at 24-hr average PM10 levels not exceeding 115 $\mu\text{g}/\text{m}^3$. When the WHO Air Quality Guidelines and the U.S. EPA standard for PM10 were developed, there were no studies available on health effects of PM10. In this review, we include nine studies documenting health effects of measured PM10 at low levels of exposure, indicating that there is now an entirely new epidemiologic database that can be evaluated in the process of revising current guidelines and standards. The low levels of exposure at which effects on health were seen underscore the urgent need for such reevaluations. — *Environ Health Perspect* 103(Suppl 2):3–13 (1995)

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Introduction

Air quality guidelines and standards for the major air pollutants ozone, sulfur dioxide, nitrogen dioxide, and suspended particulate matter are based on evidence from controlled animal exposure and controlled human and epidemiologic studies. For example, in the World Health Organization (WHO) Air Quality Guidelines for Europe (1), the quantitative evaluation of health risks of SO_2 and suspended particulate matter is largely based on epidemiologic studies; the evaluation of health risks of ozone is based on a mixture of animal and human experiments and of epidemiologic studies;

and the evaluation for NO_2 is based mostly on animal and human experiments and to some extent on epidemiologic studies of indoor NO_2 exposure. The U.S. Environmental Protection Agency (U.S. EPA) Air Quality Standards for ozone and particulate matter in air are also clearly influenced by results of epidemiologic studies (2,3). Epidemiologic studies are particularly important in defining minimum concentrations at which adverse effects on health are detectable. Nevertheless, because actual exposures are always to mixtures of pollutants, epidemiologic studies may not be able to explicitly define the causal agent in the mix of air pollutants. The composition of these mixtures varies in time and space, so that the relationship between measured concentrations of “indicator components” and health effects found in epidemiologic studies may also vary in time and space. This calls for critical appraisal of new research findings, especially those obtained in studies conducted exclusively or mostly at concentration levels below current guide-

lines. The purpose of this paper is to review epidemiologic studies published after the publication of the WHO Air Quality Guidelines for Europe in 1987, focusing on epidemiologic studies conducted at low levels of the aforementioned major ambient air pollution components. We will also restrict ourselves to investigations of effects of short-term changes in air pollution because we feel that a discussion of effects of long-term exposure requires a different approach with regard to treatment of potential confounders and other issues, which would extend both the scope and the length of this discussion beyond a reasonable length.

In the following sections, we will first give an admittedly somewhat arbitrary definition of “low levels” of air pollution. Then we will identify epidemiologic studies published after 1986 that provide information on health effects at these low concentration levels. We will briefly discuss the results of these studies, asking to what extent the findings suggest that adverse health effects occur at low levels of ambient

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air pollution. The validity of the study results will be discussed with respect to exposure assessment, treatment of time-varying potential confounders, and statistical treatment of the data.

Short-term changes in air pollution concentrations have typically been associated with changes in mortality, hospital or emergency room admissions, incidence, duration or exacerbations of respiratory and other symptoms, and changes in lung function indices. We will evaluate studies looking at these effects, in an attempt to establish whether there is coherence in observed effects (4).

Ozone

For ozone, the WHO Air Quality Guidelines specify that effects on human health such as pulmonary function changes and increased respiratory symptom reporting can be expected in exercising subjects at 1-hr average concentrations exceeding 160 to 200 $\mu\text{g}/\text{m}^3$. A 1-hr guideline in the range of 150 to 200 $\mu\text{g}/\text{m}^3$ was suggested (1). The current U.S. EPA standard is 240 $\mu\text{g}/\text{m}^3$ (2). We will therefore evaluate studies conducted at 1-hr concentrations not exceeding 240 $\mu\text{g}/\text{m}^3$.

Mortality

For ozone, no studies were identified that permit analysis of effects of low concentrations of ozone or total photochemical oxidants on mortality. A recent analysis by Kinney and Ozkaynak (5) suggested that in Los Angeles, daily mortality is associated with photochemical oxidants, but concentrations of ozone frequently exceeded 240 $\mu\text{g}/\text{m}^3$ in the observation period (1970–1979), and the authors did not attempt to censor or otherwise analyze the data to investigate whether effects persisted at low levels of exposure.

Hospital Admissions

Pönkä studied asthma admissions in Helsinki, Finland, over a 3-year period (6). Ozone concentrations were low and ranged from 0 to 90 $\mu\text{g}/\text{m}^3$ only. Other pollutants were low also, with the exception of total suspended particulate matter (TSP), which ranged from 6 to 414 $\mu\text{g}/\text{m}^3$ in the period of observation. After adjustment for temperature, asthma admissions to hospital were found to be related to ozone and several other pollutants. In a model containing temperature, NO, NO₂, CO, SO₂, ozone, and TSP simultaneously, NO, ozone, and CO alone were significant predictors of asthma visits.

Thurston et al. (7) studied the relationship between hospital admissions and

air pollution in three New York State metropolitan areas in 1988 and 1989. In 1988, maximum hourly ozone concentrations ranged from 296 to 412 $\mu\text{g}/\text{m}^3$ in the investigated areas, whereas in 1989, maximum concentrations were between 222 and 256 $\mu\text{g}/\text{m}^3$. A significant effect of ozone, with time lags ranging from 1 to 3 days, was found on total respiratory and asthma admissions in 1988. The authors reported that in 1989, coefficients were similar to those obtained in 1988, though not always significant. No specific analysis of effects at low levels was done. Since the maximum ozone concentrations per area were either slightly below or slightly above 240 $\mu\text{g}/\text{m}^3$, these results suggest that effects of ozone on hospital admissions occur at levels below 240 $\mu\text{g}/\text{m}^3$, but they do not permit a definitive conclusion. No attempt was made to separate ozone effects from effects of other components in the mixture (sulfate and strong aerosol acidity) that were also significantly associated with total respiratory and asthma admissions.

A similar study was done in Toronto in 1986 to 1988 (8). Asthma admissions were found to be related to ozone, and results were not changed when all days with concentrations exceeding 240 $\mu\text{g}/\text{m}^3$ were removed from the analysis. No attempt was made to separate ozone effects from effects of other components in the mixture (sulfate and strong aerosol acidity) that were also significantly associated with asthma admissions.

Lung Function and Other Effects

Avol et al. (9) exposed 66 exercising children in a chamber to either ambient or purified air. Ambient air contained ozone at 226 (± 6) $\mu\text{g}/\text{m}^3$, whereas in purified air, ozone was only 6 $\mu\text{g}/\text{m}^3$. No effect of ambient air on group mean lung function was observed, but when individual lung function data were regressed on estimated individual ozone doses, a significantly negative relationship emerged. To what extent these effects can be attributed solely to ozone is not clear; the ambient air the children were exposed to also contained relatively high concentrations of total suspended particulate matter at 188 (± 62) $\mu\text{g}/\text{m}^3$, but no regressions of individual lung function on individual estimated TSP doses were reported.

Spektor et al. (10) studied the relationship between ozone exposure and lung function changes in normal children participating in a summer camp. Ozone concentrations never exceeded 240 $\mu\text{g}/\text{m}^3$. The lung function indices forced vital capacity

(FVC), forced expiratory volume in 1 sec (FEV₁), peak expiratory flow (PEF), and maximum mid expiratory flow (MMEF) were all significantly and negatively associated with the ozone concentration in the hour preceding the lung function test. Notably, these results did not change when ozone concentrations exceeding 120 or 160 $\mu\text{g}/\text{m}^3$ were excluded from the analysis. The mean regression coefficient for PEF is $-3.4 \text{ ml/sec}/\mu\text{g}/\text{m}^3$. The coefficient for PEF decreased to $-2.0 \text{ ml/sec}/\mu\text{g}/\text{m}^3$ after exclusion of concentrations over 120 $\mu\text{g}/\text{m}^3$.

In another summer camp study, Spektor et al. (11) found results essentially the same as those obtained earlier (10). Maximum 1-hr ozone concentrations reached 300 $\mu\text{g}/\text{m}^3$, but the results of the regression analysis remained unchanged when ozone concentrations over 240 $\mu\text{g}/\text{m}^3$ were excluded from the analysis. In this study, a significant relationship also was found between lung function measured in the morning and the maximum 1-hr peak ozone concentration of the previous day, suggesting some persistence of the effect.

Berry et al. (12) studied children and counselors in two summer camps. Cough was reported twice as frequently, and eye irritation about one-and-a-half times as frequently on days with 1-hr maximum ozone concentrations in the range of 160 to 240 $\mu\text{g}/\text{m}^3$, compared to days with ozone concentrations lower than 160 $\mu\text{g}/\text{m}^3$. Numbers were small, however, and none of these differences reached statistical significance.

Thurston et al. (13) studied PEF and asthma symptoms daily in a weeklong summer camp for asthmatic children in 1991 and 1992. In 1991, significant effects of ozone on PEF and asthma exacerbations were found at concentrations ranging up to 320 $\mu\text{g}/\text{m}^3$. In 1992, the maximum 1-hr ozone concentration was only 126 $\mu\text{g}/\text{m}^3$, and no effects on PEF and asthma exacerbations were seen.

Kinney et al. (14) studied 154 school children in the spring of 1981. The children had 4 to 6 lung function tests over a period of 2.5 months. Ozone 1-hr maximum concentrations on those days ranged from 14 to 156 $\mu\text{g}/\text{m}^3$. There was a significantly negative relationship between ozone and various indices of lung function, including FVC, FEV₁, and MMEF. PEF was not measured in this study.

Krzyzanowski et al. (15) measured PEF three times a day in a population of 287 children and 523 adults living in Tucson, over 2-week periods for each subject. Subjects were studied during normal daily

activities. Ozone concentrations ranged from 30 to 184 $\mu\text{g}/\text{m}^3$ (1-hr maximum) during the observation period. PEF in children and adults was related to ozone concentrations; and for children, a mean coefficient of $-1.0 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$ was estimated, with larger effects seen among the asthmatics. The subjects in this study were not outdoors as much, and were not physically active as much as in the summer camp studies, which could explain the smaller mean coefficient. In addition to the lung function effects, a 30% increase in allergic or irritant symptoms (eye irritation or runny nose) was seen when the 8-hr maximum ozone concentration on the previous day was over 110 $\mu\text{g}/\text{m}^3$, as opposed to below 110 $\mu\text{g}/\text{m}^3$.

Hoek et al. (16,17) studied five hundred thirty-three 6- to 12-year-old children in Netherlands in the spring and early summer of 1989. Spirometry was repeatedly performed during school hours within this period on each child. Ozone concentrations ranged from 7 to 237 $\mu\text{g}/\text{m}^3$ in the observation period. The children were studied in a period when they were going to school and outdoor play was limited to a few afternoon hours at most on most days. All lung function indices—FVC, FEV₁, PEF, and MMEF—were significantly and negatively associated with the 1-hr maximum ozone concentration of the previous day. The mean slope for PEF was estimated at $-1.72 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$. There was no relationship between ozone levels and reports of acute respiratory symptoms.

In another study conducted in Netherlands, Hoek et al. (18) measured PEF before and after exercise in children participating in sports training or competitions. Ozone concentrations (1-hr maximum) during exercise were all below 240 $\mu\text{g}/\text{m}^3$. PEF change over the exercise periods was not related to ozone, but PEF after exercise was found to be related to the 1-hr maximum ozone concentration measured on the previous day. Ozone concentrations were found to be highly correlated with ambient temperature for some children. After exclusion of data obtained from children with ozone-temperature Pearson correlations higher than 0.6, a significantly negative mean slope of $-1.7 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$ for PEF on previous-day ozone was estimated. Exercise levels were judged to be low in this study, which may explain why effects of ozone concentrations observed during exercise were not seen.

Spektor et al. (19) studied a group of 30 adults exercising for 15 to 55 min out-

doors in air containing ozone concentrations ranging from 42 to 248 $\mu\text{g}/\text{m}^3$. There was a significantly negative relationship between ozone and lung function in this study, which persisted after all ozone concentrations higher than 160 $\mu\text{g}/\text{m}^3$ were excluded from the analysis. The mean regression coefficient for PEF of $-4.6 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$. The coefficient for PEF decreased to $-3.3 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$ after exclusion of concentrations over 160 $\mu\text{g}/\text{m}^3$.

Korrick et al. (20) studied lung function changes in subjects hiking up Mount Washington in New Hampshire under varying ozone exposure conditions. Ozone concentrations (1-hr maximum) ranged up to 188 $\mu\text{g}/\text{m}^3$. Changes in FVC and FEV₁ over the hiking period were found to be significantly associated with the ozone concentration, and changes were found to increase with increasing hike duration and with a history of wheeze.

Brunekreef et al. (21) studied a group of amateur cyclists in the summer of 1991 repeatedly during training and competition in Netherlands. Mean exercise duration was 75 min (mostly in the late afternoon or early evening). Ozone concentrations during exercise never exceeded 200 $\mu\text{g}/\text{m}^3$, and in only 3.6% of observations a value of 160 $\mu\text{g}/\text{m}^3$ was exceeded. Lung function changes over the exercise periods were found to be significantly associated with ozone concentrations, with a mean coefficient for PEF of $-3.9 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$. After excluding all ozone concentrations larger than 120 $\mu\text{g}/\text{m}^3$, the coefficients remained unchanged. Ozone exposure was also found to be related to an increase in symptom reporting, notably, shortness of breath, chest tightness, and wheeze.

In a study conducted in Switzerland, Braun-Fahrlander et al. (22) studied effects of ozone on lung function in children exercising for only 10 min in ambient air. Ozone concentrations ranged from 40 to 157 $\mu\text{g}/\text{m}^3$. A significant relationship between ozone and PEF was found, with a mean slope of $-1.3 \text{ ml}/\text{sec}/\mu\text{g}/\text{m}^3$.

Table 1 summarizes the results of the studies on ozone that were discussed in this section. Studies of the association of ozone with increased mortality at levels below 240 $\mu\text{g}/\text{m}^3$ have not been performed. There is some evidence that at concentrations lower than 240 $\mu\text{g}/\text{m}^3$, hospital admissions for asthma and other respiratory conditions are increased.

A fairly large number of recent studies document that changes in lung function occur at ozone levels sometimes well below 240 $\mu\text{g}/\text{m}^3$. Nine studies were identified that were entirely conducted at ozone 1-hr maximum concentrations below 240 $\mu\text{g}/\text{m}^3$ (10,13–22). In three studies, ozone concentrations never even exceeded 160 $\mu\text{g}/\text{m}^3$ (13,14,22). In one of the latter studies (13), no effect of ozone on lung function of asthmatic children was found, but the other two documented statistically significant effects even at these low levels of exposure. Some studies have reported analyses restricted to ozone concentrations below certain cutoff points. Even at concentrations lower than 160 (19) or 120 (10,21) $\mu\text{g}/\text{m}^3$, significant effects of ozone on lung function were seen in exercising subjects. These recent studies extend the range of ozone concentrations found to be associated with lung function changes to levels well below 240 $\mu\text{g}/\text{m}^3$ and also to levels well below the 150 to 200 $\mu\text{g}/\text{m}^3$.

Table 1. Summary of studies relating hourly ozone concentrations of less than 240 $\mu\text{g}/\text{m}^3$ with specific effects on human health.

Concentration	Category of health effects			Reference
	Hospital admissions	Symptom exacerbations	Lung function changes	
<100	+			Pönkä (6)
<240	?			Thurston et al. (7)
<240	+			Thurston et al. (8)
<240			+	Avol et al. (9)
<240		–	+	Spektor et al. (11)
<240		+		Berry et al. (12)
<240		–	+	Hoek (16); Hoek et al. (17)
<240		–	+	Hoek et al. (18)
<200			+	Krzyzanowski et al. (15)
<200			+	Korrick et al. (20)
<160			+	Spektor et al. (19)
<160			+	Kinney et al. (14)
<160			–	Thurston et al. (13)
<160			+	Braun-Fahrlander et al. (22)
<120		–	+	Spektor et al. (10)
<120		+	+	Brunekreef et al. (21)

range suggested by WHO (1) in 1987 for a proper 1-hr Guideline value.

In experimental studies, the lowest level at which significant effects of ozone on lung function of exercising subjects has been reported is $160 \mu\text{g}/\text{m}^3$, for a multi-hour exposure (23). The results of recent epidemiologic studies suggest that at lower levels, effects on lung function are still observable.

Particles and Sulfur Dioxide

Sulfur dioxide and particulate matter were evaluated jointly in the WHO Air Quality Guidelines on the basis of the observation that they usually occur together, representing a complex mixture dominated by products of fossil fuel combustion (1). The discussion of short-term effects led to the evaluation that excess mortality could be expected to occur at 24-hr levels of SO_2 and black smoke both exceeding $500 \mu\text{g}/\text{m}^3$. Likewise, excess morbidity was suggested to occur at SO_2 and black smoke levels both exceeding $250 \mu\text{g}/\text{m}^3$, and temporary decrements in lung function were suggested to occur at levels of TSP exceeding $180 \mu\text{g}/\text{m}^3$, in the presence of elevated concentrations of SO_2 (exact levels not specified). Although at the time no studies relating health effects to inhalable particles (PM10) had been published, it was suggested that $180 \mu\text{g}/\text{m}^3$ of TSP would be equivalent to $110 \mu\text{g}/\text{m}^3$ of PM10. Taking into account a margin of protection of about 1.5, 24-hr average guidelines of $125 \mu\text{g}/\text{m}^3$ for SO_2 , in combination with $125 \mu\text{g}/\text{m}^3$ of black smoke, or $120 \mu\text{g}/\text{m}^3$ of TSP, or $70 \mu\text{g}/\text{m}^3$ of PM10, were proposed. In 1987, the U.S. EPA promulgated a 24-hour PM10 National Ambient Air Quality Standard of $150 \mu\text{g}/\text{m}^3$ (3), without consideration for concurrent levels of SO_2 . We will focus on studies conducted at 24-hr SO_2 concentrations not exceeding $200 \mu\text{g}/\text{m}^3$, black smoke and TSP levels not exceeding $200 \mu\text{g}/\text{m}^3$, and PM10 levels not exceeding $150 \mu\text{g}/\text{m}^3$, either alone or in combination.

As many recent studies have emphasized that particles may exert adverse effects on health in the absence of high levels of SO_2 , studies on particles will be discussed first, and studies on SO_2 afterward.

Particles

Mortality

Several recent studies have addressed the relationship between particulate air pollution and daily mortality at low levels of exposure (24–29).

Schwartz and Marcus reanalyzed mortality data from London (24) for the winters of 1958 to 1972. In a graphic analysis, they found no evidence for a threshold in the relationship between black smoke and total daily mortality, down to the lowest levels of $20 \mu\text{g}/\text{m}^3$. No interaction between black smoke and SO_2 was found, and after adjustment for weather variables and SO_2 , the effect of smoke remained significant, whereas there was no independent effect of SO_2 after adjustment for black smoke. The graphic analysis suggesting effects at very low levels was not supported by a specific statistical analysis using censored data, so that it remains unclear what the lowest level of black smoke was below which significant relationships between air pollution and daily mortality could be found.

Schwartz (25) analyzed the relationship between air pollution and daily mortality in Detroit, for 1973 to 1982. TSP was measured every sixth day, and its value for the other days was estimated from a regression model containing visibility data and other variables. A significant relationship between TSP and mortality was found that was independent of other pollutants (ozone and SO_2) and of weather variables. No independent effects of either ozone or SO_2 were found. A graphic analysis suggested that there was no threshold to this effect. After excluding all TSP values under 46 and over $137 \mu\text{g}/\text{m}^3$, the results were unchanged, suggesting that effects on mortality are observable at 24-hr average TSP levels below $137 \mu\text{g}/\text{m}^3$. The estimated magnitude of the effect was a 6% increase in mortality associated with a $100 \mu\text{g}/\text{m}^3$ increase in TSP.

Pope et al. (26) studied daily mortality in relationship with PM10 pollution in Utah Valley for the period of April 1985 to December 1989. A local steel mill is a major source of particulate air pollution in the area, in which concentrations of ozone, SO_2 , and NO_2 are generally low. Respiratory and cardiovascular mortality were found to be related to PM10. Average 24-hr concentrations ranged up to $365 \mu\text{g}/\text{m}^3$ in the observation period, but a graphic and tabular analysis suggested that effects on mortality could be seen at levels below $100 \mu\text{g}/\text{m}^3$. No statistical evaluation using censored data was made, however.

Schwartz and Dockery (27) studied mortality in Philadelphia over the years 1973 to 1980. The second-highest 24-hr average TSP concentration in this period was $222 \mu\text{g}/\text{m}^3$. Daily mortality was found to be related to TSP. There was no interaction with SO_2 , and the effect of TSP was

independent of SO_2 . The estimated effects were larger for respiratory and cardiovascular deaths than for other diagnoses, and they were also larger for subjects over 65 years of age than for younger subjects. A graphic analysis suggested that the effect was already detectable at levels below $100 \mu\text{g}/\text{m}^3$, but no attempt was made to do an analysis with data censored to below certain cutoff points for TSP.

The same authors have also published a very similar analysis of mortality data from Steubenville, Ohio (28). Again, a graphic analysis suggested effects of TSP on mortality at levels below $100 \mu\text{g}/\text{m}^3$; but no censoring was applied to the data that would permit identification of a threshold level below which no significant relationship between mortality and TSP exists.

Dockery et al. (29) have also published an analysis of daily mortality in St. Louis, Missouri, and the counties surrounding Kingston/Harriman, Tennessee. During the period of observation (September 1985–August 1986), 24-hr average PM10 levels ranged from 1 to $97 \mu\text{g}/\text{m}^3$ in St. Louis, and from 4 to $67 \mu\text{g}/\text{m}^3$ in Kingston/Harriman. Even at these low levels, a relationship between PM10 and mortality was found that was statistically significant for St. Louis. The estimated coefficient for Kingston/Harriman was insignificant, but of similar magnitude. A number of gaseous air pollution components (SO_2 , NO_2 , ozone) were evaluated as well, but none of these was found to be significantly associated with mortality.

Hospital Admissions

Schwartz et al. (30) investigated the variation in daily visits to hospitals or pediatricians for croup symptoms and obstructive bronchitis in children in five German towns in the mid-1980s. Maximum pollutant concentrations were not given, but 90-percentiles for TSP ranged from 41 to $118 \mu\text{g}/\text{m}^3$ in the five cities, suggesting that most if not all of the concentrations were lower than $200 \mu\text{g}/\text{m}^3$ in the period of observation. Visits for croup (but not for obstructive bronchitis) were found to be associated with TSP, NO_2 , and SO_2 in models containing only one pollutant. In two-pollutant models, SO_2 and NO_2 became insignificant, whereas TSP remained significant in the model also containing SO_2 . A graphic analysis suggested that at TSP levels below $100 \mu\text{g}/\text{m}^3$, the risk of croup increased.

Diaz-Caneja et al. (31) studied hospital admissions for chronic obstructive pulmonary disease (COPD) in Santander,

Spain, in relation with daily SO_2 and black smoke concentrations. The mean and range of the pollutant concentrations were not given, but COPD admissions were found to be related to both SO_2 and black smoke. A graphic analysis suggested that admissions were already increased at black smoke levels exceeding $40 \mu\text{g}/\text{m}^3$. There was also a relationship with SO_2 , but this appeared to be less strong than for black smoke. No attempt was made to separate the two pollutants in the analysis.

Sunyer et al. (32,33) studied emergency room admissions for COPD in Barcelona, Spain. Black smoke concentrations ranged from 39 to $310 \mu\text{g}/\text{m}^3$, and SO_2 from 17 to $160 \mu\text{g}/\text{m}^3$. A significant relationship between the number of emergency room admissions and both SO_2 and black smoke was found. The relationship persisted when all SO_2 concentrations above $72 \mu\text{g}/\text{m}^3$ were removed from the analysis and also when all black smoke concentrations over $100 \mu\text{g}/\text{m}^3$ were removed. The relationships with SO_2 and black smoke appeared to be independent of each other, and the relationship with SO_2 was apparent in all seasons, whereas the relationship with black smoke was most clear in winter.

Schwartz et al. (34) studied hospital emergency room visits for asthma in Seattle over a 13-month period from September 1989 to September 1990. Average 24-hr PM10 concentrations ranged from 6 to $103 \mu\text{g}/\text{m}^3$. Asthma visits by subjects under 65 years of age were significantly associated with PM10 measured on the previous day, after adjustment for weather variables and a number of other potential confounders. A graphic and tabular analysis suggested that an increase in asthma visits could already be observed at levels below $24 \mu\text{g}/\text{m}^3$. SO_2 and ozone were not found to be related to asthma visits. SO_2 concentrations never exceeded $81 \mu\text{g}/\text{m}^3$, and ozone data were only available for a 4-month period within the period of observation.

Walter et al. (35) studied hospital admissions for asthma and acute respiratory disease over a 2-year period in Birmingham, England. Air pollution exposure was expressed as weekly average black smoke and SO_2 concentrations. Black smoke concentrations ranged from 10 to over $60 \mu\text{g}/\text{m}^3$, SO_2 concentrations from 20 to $100 \mu\text{g}/\text{m}^3$. Significant relationships were found between hospital admissions and daily as well as weekly black smoke and SO_2 concentrations in the winter period. These relationships were found to be independent of weather conditions. There

was no attempt to separate effects of black smoke from those of SO_2 .

Lung Function and Other Effects

Ostro et al. (36) studied a panel of asthmatic patients in Denver, Colorado, in the winter of 1987/1988. Average 24-hr concentrations of PM2.5, a measure of respirable particulate matter, ranged from 1 to $73 \mu\text{g}/\text{m}^3$. PM2.5 concentrations were found to be related to asthma rating in this panel after adjustment for autocorrelation, temperature, and a number of other potential confounders.

Forsberg et al. (37) studied a panel of asthmatic patients living in northern Sweden. In the area, wood is used extensively for residential heating. In the period of observation (March and April), SO_2 concentrations ranged from 1 to $13 \mu\text{g}/\text{m}^3$, and black smoke from 1 to $21 \mu\text{g}/\text{m}^3$. Daily reports of shortness of breath were related to black smoke after adjustment for weather variables. In one location 1 km away from the study area, 12-hr TSP samples were taken, and a maximum concentration of $101 \mu\text{g}/\text{m}^3$ was found, suggesting that the actual particle mass concentration may have been much higher than the black smoke concentration in the area.

Braun-Fahrlander et al. (38) studied daily changes in respiratory symptoms in 625 young children living in two Swiss cities. Average 24-hr TSP levels ranged from 30 to $117 \mu\text{g}/\text{m}^3$. The reported incidence of upper respiratory symptoms was found to be associated with TSP concentrations measured on the previous day. A graphic analysis suggested that this effect could be observed at TSP levels well below $100 \mu\text{g}/\text{m}^3$.

Pope et al. (39) studied daily changes in lung function and acute respiratory symptoms in a panel of subjects living in Utah Valley, Utah, where a large steel mill causes increased concentrations of PM10 but not of other pollutants. Subjects included a sample of wheezing school children and a sample of asthma patients 8 to 72 years of age. The observation period included the winter months of 1989/1990. The 24-hr PM10 concentrations ranged from 11 to $195 \mu\text{g}/\text{m}^3$, and on only 2 days, a concentration of $150 \mu\text{g}/\text{m}^3$ was exceeded. PEF was found to be related to PM10 concentrations in the preceding days. Respiratory symptoms and asthma medication used increased with increasing PM10 concentrations in the school-based sample of children. In the asthma patients, only the use of extra asthma medications was found to be associated with PM10. After

excluding the 2 days with PM10 concentrations over $150 \mu\text{g}/\text{m}^3$, the highest PM10 concentration was $114 \mu\text{g}/\text{m}^3$. The relationship between PEF and PM10 remained unchanged after this exclusion.

Pope and Dockery (40) studied panels of symptomatic and asymptomatic children in Utah Valley in the winter of 1990/1991. The 24-hr PM10 concentrations ranged from 7 to $251 \mu\text{g}/\text{m}^3$. On 14 days during the study period, a level of $150 \mu\text{g}/\text{m}^3$ was exceeded. PEF was decreased, and the reporting of respiratory symptoms increased in both panels when PM10 concentrations increased. All observations from days with or immediately following days with PM10 concentrations over $150 \mu\text{g}/\text{m}^3$ were excluded from some of the analyses. The results remained essentially unchanged. A tabular analysis further suggested that PEF was decreased, and respiratory symptoms increased, at PM10 concentrations exceeding $39 \mu\text{g}/\text{m}^3$.

In another study from the Utah Valley, Ransom and Pope (41) investigated elementary school absences in relationship to PM10 pollution over a period of 6 years, 1985 to 1990. The highest PM10 concentration observed in this period was $365 \mu\text{g}/\text{m}^3$, and exceeded $150 \mu\text{g}/\text{m}^3$ on approximately 10 days each year. School absenteeism was found to be related to 4-week moving average PM10 concentrations, after adjustment for weather variables and a number of other potential confounders. The relationships generally remained after excluding observations obtained on days when PM10 had exceeded $150 \mu\text{g}/\text{m}^3$ within the previous 4 weeks.

Roemer et al. (42) studied a panel of children with chronic respiratory symptoms in Netherlands in the winter of 1990/1991. Average 24-hr PM10 concentrations exceeded $150 \mu\text{g}/\text{m}^3$ on 1 day only in the observation period, reaching $171 \mu\text{g}/\text{m}^3$. SO_2 levels were never higher than $105 \mu\text{g}/\text{m}^3$, and black smoke concentrations (24-hr averages) ranged from 2 to $120 \mu\text{g}/\text{m}^3$. Daily changes in PEF, asthma attacks, wheeze, and bronchodilator use were found to be associated with PM10, black smoke, and SO_2 . A tabular analysis suggested that effects on wheeze and bronchodilator use were observable from concentrations exceeding $40 \mu\text{g}/\text{m}^3$. SO_2 , black smoke, and PM10 were highly correlated in this data set, so that effects of particles and SO_2 could not be separated.

A group of school children not participating in the above study was investigated in this period with repeated spirometry (43,44). FVC and FEV_1 were associated

with PM₁₀, SO₂, and black smoke. There was no relationship between air pollution and acute respiratory symptoms in this panel.

Hoek and Brunekreef (45) studied panels of school children in the winters of 1988 to 1990 in Netherlands. All children were tested repeatedly with spirometry over periods of about 10 to 15 weeks. In the observation period, 24-hr PM₁₀ concentrations ranged from 14 to 126 $\mu\text{g}/\text{m}^3$, SO₂ from 0 to 94 $\mu\text{g}/\text{m}^3$, and NO₂ from 2 to 70 $\mu\text{g}/\text{m}^3$. PEF and MMEF were found to be negatively associated with PM₁₀ and NO₂ concentrations measured either on the same day or the day before the lung function tests, after adjustment for ambient temperature.

Table 2 summarizes the results of the studies on particles that were discussed in this section. These studies indicate that increases in daily mortality have been found in a situation where measured PM₁₀ concentrations never exceeded 100 $\mu\text{g}/\text{m}^3$ (29), in a situation where TSP concentrations were censored to below 137 $\mu\text{g}/\text{m}^3$ (25), in three situations where a graphic analysis suggested that effects on mortality were present at levels below 100 $\mu\text{g}/\text{m}^3$ of either PM₁₀ (26) or TSP (27, 28). A reanalysis of data from London further suggested that daily mortality was related to black smoke without evidence of a threshold at levels down to 20 $\mu\text{g}/\text{m}^3$ (24).

Hospital admissions for respiratory disorders were found to be related to low concentrations of particles in five studies. Most

convincing are the studies from Seattle (34), where measured PM₁₀ levels never exceeded 103 $\mu\text{g}/\text{m}^3$ and Birmingham, England (35), where the weekly average black smoke concentration never exceeded 60 $\mu\text{g}/\text{m}^3$. Studies from Barcelona have documented effects at black smoke levels censored to below 150 $\mu\text{g}/\text{m}^3$ (32,33), and a study from Germany suggested effects on hospital and pediatrician croup visits at TSP levels below 100 $\mu\text{g}/\text{m}^3$ by graphic analysis (30).

Effects of particulate pollution on acute respiratory symptoms, lung function, and school absenteeism have been found in several recent studies. Some of these were conducted entirely at concentration levels: black smoke < 120 $\mu\text{g}/\text{m}^3$ (42–44), black smoke < 25 $\mu\text{g}/\text{m}^3$ (37), PM₁₀ < 130 $\mu\text{g}/\text{m}^3$ (45). Other studies have employed censoring in the analysis of the data: to below 150 $\mu\text{g}/\text{m}^3$ PM₁₀ (40,41) or < 115 $\mu\text{g}/\text{m}^3$ (39). One study (38) suggested effects on acute respiratory symptoms at TSP levels below 100 $\mu\text{g}/\text{m}^3$ by graphic analysis.

The variety of particulate air pollution measures employed in these studies makes evaluation in terms of one single indicator somewhat problematic. Relationships between the three primary indicators PM₁₀, TSP, and black smoke have been suggested (46) as PM₁₀ = BS and PM₁₀ = TSP × 0.55. A proportionality between PM₁₀ and PM_{2.5} of 0.6 was suggested. However, such relationships may vary from place to place and with time,

depending on the contribution of local sources. Nevertheless, on the basis of these relationships the data summarized in Table 2 suggest that particulate air pollution is associated with daily mortality, hospital admissions, symptom exacerbations, and lung function changes at levels not exceeding 100 $\mu\text{g}/\text{m}^3$, expressed as PM₁₀. Indeed, several of the graphic and tabular analyses suggest that it is difficult to establish a threshold below which such effects would not be found to be associated with particles. So far, studies have simply not been reported that have specifically analyzed associations between particles and acute health events using cutoff points below 100 $\mu\text{g}/\text{m}^3$.

Sulfur Oxide

Mortality

Mackenbach et al. (47) analyzed daily mortality in Netherlands over the years 1979 to 1987, in relation to SO₂. In the whole period, there were only 20 days (out of 3288) on which SO₂ exceeded 200 $\mu\text{g}/\text{m}^3$. A graphic analysis suggested that SO₂ was related to daily mortality without evidence for a threshold. However, after adjustment for a range of weather variables, the SO₂ effect changed sign into a significant negative relationship with mortality. The authors concluded that the unadjusted relationship between SO₂ and mortality was entirely due to confounding by weather variables. However, so many lagged weather variables were entered into the analysis that the significant relationship between unlagged cold temperature and mortality changed sign also, making the results of the adjusted analysis rather difficult to interpret. Data for particulate air pollution were not available, so that it was not possible to evaluate the association between particles and mortality in this data set.

In Barcelona, mortality was found to be associated with SO₂ in the same period in which relationships with hospital admissions were found (48). A 100 $\mu\text{g}/\text{m}^3$ increase of daily average SO₂ concentrations in summer was found to be associated with a 15% increase in cardiovascular mortality. As reported (32,33), SO₂ concentrations never exceeded 160 $\mu\text{g}/\text{m}^3$.

Hospital Admissions

Bates et al. (49) investigated hospital emergency visits for respiratory conditions in Vancouver, Canada, over a period of more than two years in 1984 to 1986. Pollution data were reported in graphic form and were expressed as hourly rather

Table 2. Summary of studies relating 24-hr average particle concentrations of less than 200 $\mu\text{g}/\text{m}^3$ (TSP or black smoke) or 150 $\mu\text{g}/\text{m}^3$ (PM₁₀) with specific effects on human health.

Concentration	Category of health effect				Reference
	Mortality	Hospital admissions	Symptom exacerbations	Lung function changes	
? (BS)	+				Schwartz and Marcus (24)
< 137, TSP	+				Schwartz (25)
< 100 (PM ₁₀)	+				Pope et al. (26)
< 100 (TSP)	+				Schwartz and Dockery (27,28)
< 100 (PM ₁₀)	+				Dockery et al. (29)
< 100 (TSP)		+			Schwartz et al. (30)
? (BS)		+			Diaz-Caneja et al. (31)
< 150 (BS)		+			Sunyer et al. (32,33)
< 105 (PM ₁₀)		+			Schwartz et al. (34)
< 60 (BS, weekly)		+			Walter et al. (35)
< 115 (PM ₁₀)			+	+	Pope et al. (39)
< 75 (PM _{2.5})			+		Ostro et al. (36)
< 100 (TSP)			+		Braun-Fahrlander et al. (38)
< 150 (PM ₁₀)			+	+	Pope and Dockery (40)
< 150 (PM ₁₀)			+		Ransom and Pope (41)
< 120 (BS), < 175 (PM ₁₀)			+	+	Roemer et al. (42)
					Brunekreef and Hoek (43)
					Hoek and Brunekreef (44)
< 25 (BS)			+		Forsberg et al. (37)
< 130 (PM ₁₀)			–	+	Hoek and Brunekreef (45)

than 24-hr data. The highest 1-hr maximum for SO₂ was about 300 µg/m³, so it can be assumed that the vast majority (if not all) of the 24-hr averages were below 200 µg/m³. Respiratory and asthma visits were found to be correlated with SO₂ in both the winter and the summer seasons. No data on particles were reported.

Lipfert and Hammerstrom (50) analyzed hospital admission data obtained over a 6-year period in southern Ontario, Canada. Respiratory admissions were found to be related to SO₂ and ozone, at concentrations that were said to be "generally within U.S. ambient standards," but otherwise unspecified. Consequently, this study cannot be used to make further quantitative inferences.

The studies conducted by Sunyer et al. in Barcelona (32,33) and Diaz-Caneja et al. in Santander (31) have already been discussed; both studies found associations between COPD admissions and low levels of SO₂.

Lung Function and Other Effects

Vedal et al. (51) studied three panels of children in the Chestnut Ridge region in western Pennsylvania over an 8-month period in the fall, winter, and spring of 1980/1981. Panels were selected to include healthy children, wheezing children, or children with chronic cough or phlegm without wheeze. Maximum hourly SO₂ concentrations ranged from 18 to 176 µg/m³. Maximum hourly NO₂ and ozone concentrations never exceeded 79 and 129 µg/m³, respectively. Neither acute respiratory symptoms nor PEF was found to be related to pollutant concentrations. However, the authors made adjustments for symptoms reported on the previous day, or for PEF on the previous day, in an attempt to adjust for autocorrelation of the serial symptom and lung function data. This may have led to some overadjustment of the findings. The results of this study are therefore difficult to compare to other studies.

Pönkä (52) studied the incidence of respiratory tract infections reported by health centers, and absenteeism from school or work in Helsinki in 1987. There, 24-hr SO₂ values never exceeded 130 µg/m³. The incidence of upper respiratory tract infections reported by the health centers was found to be related to SO₂, after adjustment for temperature. There was no relationship with NO₂; potential relationships with TSP, known to be relatively high in Helsinki, were not explored.

Moseholm et al. (53) studied a panel of nonallergic asthmatic patients in two

Danish cities over an 8-month period in the fall, winter, and spring of 1987 to 1988. SO₂ concentrations never exceeded 81 µg/m³, and NO₂ concentrations were all below 95 µg/m³ as 24-hr averages. To take collinearity of some of the variables and autocorrelation properly into account, data were analyzed by a novel "neural network" approach. The results suggested that PEF decreased when either SO₂ or NO₂ exceeded 40 µg/m³. No data on other pollutants potentially covarying with SO₂ and/or NO₂ were given.

Table 3 summarizes the results of the studies on SO₂ discussed in this section. The evidence from these studies on low-level effects of SO₂ is less abundant and strong than from studies on ozone and particles. In the mortality study by Mackenbach et al. (47), no adjustment could be made for particulate air pollution, and the strategy followed to aggressively adjust for weather variables seems unbalanced. Adjustment for potential particle effects was absent from the hospital admission study by Bates et al. (49) as well. An independent effect of low SO₂ concentrations was found by Sunyer et al. in Barcelona (32,33). However, the authors themselves comment that the measure of particulate matter they used (black smoke) was poorly related to TSP, especially in summer; and it remains unclear to what extent adjustment for potential particle effects was sufficient in their data. Adjustment for potential confounding by particles was done in none of the cited studies looking at lung function and symptom effects. Although some of these studies suggested effects to occur at low to very low levels of SO₂, the conclusions with regard to SO₂ will have to remain tentative in light of the generally stronger evidence of effects of particles that are

independent of effects of the gaseous components discussed in this section. Virtually no studies have evaluated independent effects of low levels of NO₂ in the past few years.

Discussion

In the last 6 years, many epidemiologic studies have been reported that suggest that daily variations in exposure to the major air pollution components ozone, particulate matter, and SO₂ are associated with health effects ranging from increased mortality and hospital admissions to subtle changes in lung function at low to very low concentrations. Indeed, several studies have suggested that for some of these effects, it is difficult to establish any threshold at all. Before accepting the potentially large public health implications of these recent findings, the validity of the study results needs to be discussed with respect to exposure assessment, treatment of time-varying potential confounders, and statistical treatment of the data. Rather than trying to summarize the often extensive discussions on these topics contained in the original papers, we will point out some common strengths and weaknesses in the studies discussed in the previous sections.

Exposure Assessment

The studies discussed in this article have in common that they focus on time-varying exposures and health effects. Ideally, one would like to know the temporal development of personal exposure for all subjects studied. In practice, this has not been feasible in the studies reviewed here. The best exposure assessment was probably made in some of the investigations in which effects of ozone on subjects exercising outdoors were studied (9-13,18-22). By focusing on subjects exercising outdoors, complications

Table 3. Summary of studies relating 24-hr average SO₂ concentrations of less than 200 µg/m³ or 24-hr average NO₂ concentrations of less than 150 µg/m³ with specific effects on human health.

Concentration	Category of health effect				Reference
	Mortality	Hospital admissions	Symptom exacerbations	Lung function changes	
<200 (SO ₂ , >99% of days)	—				Mackenbach et al. (47)
<200 ? (SO ₂)		+			Saez et al. (48)
<72 (SO ₂)		+			Sunyer et al. (32,33)
<176 (SO ₂)					
<79 (NO ₂)			—		Lipfert et al. (50)
<130 (SO ₂)			+		Vedal et al. (51)
<81 (SO ₂)					
<95 (NO ₂)			+	+	Pönkä (52)
<100 (SO ₂)					Moseholm et al. (53)

due to the sometimes large differences between indoor and outdoor ozone concentrations are avoided. On the other extreme are studies in which daily mortality or hospital admissions in large areas have been linked to air pollution concentrations measured at only one location, sometimes not even on a daily basis. Such studies rely on existing mortality or hospital admission registrations, which usually do not permit identification of the whereabouts of the affected individuals in the days before they died or were admitted to the hospital. These subjects were presumably already diseased and may have been spending most if not all of their time indoors before they died or were admitted to a hospital. Because indoor concentrations for all pollutants discussed in this article may be markedly different from outdoors, there is understandable concern about the validity of exposure assessments based on measurements made at one or a few outdoor locations (54). This concern is further increased by the poor correlation seen between personal exposure measurements and ambient concentrations in some studies (55). However, most of these personal monitoring studies were cross-sectional in design, and there is virtually no empirical data on the correlation between personal exposure measurements and ambient concentrations as they develop over time. In one study, indoor particle and NO₂ concentrations were shown to follow ambient concentrations closely when an air pollution episode occurred, regardless of the presence of indoor sources of these pollutants (56). Until the issue of the correlation in time between personal and ambient exposure has been solved, it will not be possible to conclude that ambient concentration measurements are related to personal exposure measurements to such an extent that relationships between ambient concentrations and health events are plausible. Misclassification of exposure in studies on short-term health effects is likely to be non-differential and would bias the effect estimates toward the null rather than away from it.

Treatment of Confounders Varying with Time

The advantage of time series studies is that many of the variables that may confound relationships between air pollution and chronic health effects cannot confound short-term temporal relationships between air pollution and health because they have no short-term variation in time. Examples of such variables are gender, smoking

habits, socioeconomic status, etc. Nevertheless, other determinants of mortality, hospital admissions, acute symptom exacerbations, and lung function changes do vary over time, and these determinants need to be taken into account. Important time-varying potential confounders are weather variables and infectious disease epidemics that may be causally unrelated to air pollution changes. Few of the studies cited in this article have failed to take weather variables into account in the analysis of the data. However, there has been no uniform method of doing so, and the number of weather variables taken into account has varied markedly from study to study. An extreme example is the study by Mackenbach et al. (47), in which 15 weather variables of different time lags were included in the statistical model. Other investigators have taken a more balanced approach in sorting out the independent effects of weather and pollution.

Failure to adjust for confounders that vary in time may lead to either under- or overestimation of the effect of air pollution.

Statistical Treatment of the Data

Health end points such as daily mortality, hospital admissions, or respiratory symptom reports are often observed to be correlated day to day (autocorrelation). This is not because a health event such as a death on one day is causally related to similar health events on the next day. Rather, the underlying causes such as infectious disease, weather, or air pollution tend to be highly correlated day to day. Therefore, an appropriate model of a time series of health events should show no autocorrelation in the residuals. Autocorrelation of the model residuals is an indication of incomplete or inadequate specification of the causal associations, which implies that confounding of the air pollution associations by unmeasured or misspecified covariates is possible. One solution is to include a specification of the autocorrelation in the model, as has been done in almost all of the studies reviewed. However, it should be recognized that this may lead to instability of the estimated air pollution associations because of the high day to day correlation of the air pollution exposures. Ideally, the optimal model of air pollution would exhibit no autocorrelation of the residuals. Nevertheless, the inclusion of autocorrelation effects in the model is generally felt to produce a conservative estimate of the air pollution effect size and standard error.

Many of these analyses have considered health end points that are clearly not

Gaussian in their distribution, and concern has been raised regarding the appropriate transformations of the data and specific analytic methods. A related issue has been concern for methods for removing seasonal or other long-wave length patterns in the data before evaluating short-term effects. An important principle to consider is that statistics is only a tool that allows us to model reality. All statistical techniques provide approximations of the true associations. The validity of the estimates depends on how well the real data fit the assumptions of the statistical method. Thus it is wrong to suggest that a specific statistical method provides the "right" estimate of association. In fact, a result that is sensitive to the statistical method being used should be viewed with some skepticism; for example, air pollution associations should be robust to the analytic methods used. This is the case for the health end points discussed here. New analysis techniques such as "neural network" methods (53) need to be considered in the context of more traditional methods of analysis for this reason.

Public Health Implications

The health effects found to be associated with daily variations in the concentration of common air pollutants vary from changes in daily mortality to small, reversible changes in lung function. For particles especially, the body of evidence suggests that effects on mortality, hospital admissions, exacerbation of respiratory symptoms, and lung function all occur at comparable, low levels of exposure. Daily counts of mortality and hospital admissions for COPD or asthma are low, so the number of subjects affected by air pollution on any given day is low as well, compared to the size of the population. In contrast, transient effects on lung function may be observed in the majority of the population, and symptom exacerbation may be detected in asthmatics and COPD patients, who may comprise 5 to 10% of the population. The apparent paradox of effects of very different severity occurring at similar levels of exposure can therefore be solved by taking the frequency of occurrence into account. Small changes in lung function, or slight exacerbations of symptoms, that can easily be tolerated by healthy subjects or even mildly diseased subjects may lead to a need for acute hospitalization among the more severely ill and may even become life threatening among those who are in very bad health already. Of course, this raises the question of how serious the observed relationships between particulate air pollution

and daily mortality are from a public health point of view. The effects on mortality tend to be greater among the elderly, although they are not restricted to the oldest age categories. If daily variations of particulate matter at a low level lead to some "harvesting" effect implying that terminally ill subjects die a few days or weeks earlier than they would have, the public health importance is not as great as when subjects in all age classes and in various states of health are affected. Unfortunately, little is known about the subjects making up the slight excesses in daily mortality associated with air pollution. We do know that at much higher levels, such as those observed in the London smog episode of 1952, some subjects suddenly died on the streets or at work (57). There is a need to gain more insight into the number of days or years of lost life associated with particulate-matter air pollution, so that the public health implications of these associations can be assessed more fully. In this respect, a recent report from the United States (58) offers intriguing observations. In a follow-up study extending over a 16-year period, low levels of particulate-matter pollution were found to be associated with mortality independent of smoking, occupational exposure, body mass index, age, sex, and education. Yearly average inhalable particulate matter levels (measured as either PM₁₅ or PM₁₀ in the study) ranged from 18 to 47 $\mu\text{g}/\text{m}^3$ with little trend over time, and the relative risk, comparing the most polluted city with the least polluted city, was 1.26. These new data suggest that the associations found in the daily time series studies may imply a significant loss of life expectancy.

Quantitatively, the relationships between daily variations in particulate-matter air pollution and mortality have been expressed in several papers as percentage

increase in mortality associated with a certain increase in PM pollution. The magnitude of the increase has been estimated to range from 4 to 7% per 100 $\mu\text{g}/\text{m}^3$ TSP (25,27,28) and 16% per 100 $\mu\text{g}/\text{m}^3$ PM₁₀ (26,29). All of these were studies conducted in the United States, and when we take a conversion factor of 0.55 (PM₁₀/TSP, cf. above) into account, the TSP coefficients translate into estimated PM₁₀ effects of 7 to 13% per 100 $\mu\text{g}/\text{m}^3$. The consistency of these effect estimates is high.

For hospital admissions, effects have been estimated at a 24% increase of COPD admissions per 100 $\mu\text{g}/\text{m}^3$ in Barcelona (32,33), and a 40% increase of asthma admissions per 100 $\mu\text{g}/\text{m}^3$ PM₁₀ in Seattle (34). There are no data to make a reliable conversion of black smoke into PM₁₀ for Barcelona, but if the 1:1 relationship mentioned earlier were valid there as well, the consistency of the effect estimates from these two separate studies is again high.

Effects of PM₁₀ on peak flow of panels of children were reported in five recent papers (39,40,42,44,45). Estimated effects ranged from -40 to -110 ml/sec peak flow change per 100 $\mu\text{g}/\text{m}^3$ PM₁₀—again a remarkable consistency over five independent study populations. Such changes represent a mean change in peak flow on the order of 2 to 4% per 100 $\mu\text{g}/\text{m}^3$ PM₁₀, which in itself is not large; but especially in panels of asthmatic children, these changes have been found to be accompanied by significant increases in acute respiratory symptoms and/or medication use (39,40, 42).

Quantitative exposure-response relationships for ozone are mostly available for effects on short-term changes in lung function, notably, peak flow (10,11,15,17-19, 21,22). The estimated coefficients range from -100 ml/sec per 100 $\mu\text{g}/\text{m}^3$ of ozone

to -460 ml/sec per 100 $\mu\text{g}/\text{m}^3$. The higher coefficients were found in studies among exercising adults. These coefficients represent seemingly larger effects of ozone than of particles on lung function, of a 100 $\mu\text{g}/\text{m}^3$ change. However, there is less evidence of effects of ozone on acute symptoms and medication use.

Conclusions

Since the development of the WHO Air Quality Guidelines for Europe, a large number of epidemiologic studies have been published documenting effects of major air pollutants on health at concentrations below existing guidelines and standards.

For ambient ozone, effects on lung function of subjects exercising outdoors have been documented at 1-hr maximum levels not exceeding 120 $\mu\text{g}/\text{m}^3$, i.e., half the current U.S. EPA standard.

Several studies are now available documenting effects of particulate air pollution on health in the virtual absence of SO₂. Effects on mortality and hospital admissions for asthma have been documented at levels not exceeding 100 $\mu\text{g}/\text{m}^3$, expressed as 24-hr average PM₁₀ concentration. Effects on lung function, acute respiratory symptoms, and medication use have been found at 24-hr average PM₁₀ levels not exceeding 115 $\mu\text{g}/\text{m}^3$. When the WHO Air Quality Guidelines and the U.S. EPA standard for PM₁₀ were developed, there were no studies available on health effects of PM₁₀. In this review, we have included nine studies documenting health effects of measured PM₁₀ at low levels of exposure, indicating that there is now an entirely new epidemiologic database that can be evaluated in the process of revising current guidelines and standards. The low levels of exposure at which effects on health were seen underscore the urgent need for such reevaluations.

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